

Rate-Distortion Models for Error Resilient Video Transcoding

Field of the Invention

[01] This invention relates generally to transcoding videos, and more particularly to rate and distortion models for allocation of bits used to code the video source and bits that are applied for error resilience.

Background of the Invention

[02] Transmitting a video bitstream through wireless channels is a challenging problem due to limitations in bandwidth and a noisy channel. If a video is originally coded at a bit rate greater than an available bandwidth in a wireless channel, then the videos must first be transcoded to a lower bit rate, prior to transmission. Because a noisy channel can easily corrupt a quality of the video, there is also a need to make the encoded video bitstream resilient to transmission errors, even though the overall number of bits allocated to the bitstream is reduced.

[03] Two primary methods used for error-resilience video encoding are resynchronization marker insertion and intra-block insertion (intra-refresh). Both methods are effective at localizing errors. If the errors are localized, then recovery from errors is facilitated.

[04] Resynchronization inserts periodic markers so that when an error occurs, decoding can be restarted at a point where the last resynchronization marker was inserted. In this way, errors are spatially localized. There are two

basic approaches for inserting synchronization markers: a group-of-block (GOB) based approach, which is adopted in the H.261/H.263 standard, and a packet-based approach, which is adopted in the MPEG-4 standard.

[05] In the GOB-based approach, a GOB header is inserted periodically after a certain number of macroblocks (MBs). In the packet-based approach, header information is placed at the start of each packet. Because the way the packets are formed is based on the number of bits, the packet-based approach is generally more uniform than the GOB-based approach.

[06] While resynchronization marker insertion is suitable to provide a spatial localization of errors, the insertion of intra MBs is used to provide a temporal localization of errors by decreasing the temporal dependency in the encoded video bitstream.

[07] A number of error resilience video encoding methods are known. In “Error-resilient transcoding for video over wireless channels,” IEEE Journal on Selected Areas in Communications,” vol. 18, no. 6, pp. 1063–1074, 2000 by Reyes, et al., optimal bit allocation between error resilience insertion and video encoding is achieved by modeling the rate-distortion of error propagation due to channel errors. However, that method assumes that the actual rate-distortion characteristics of the video are known, which makes the optimization difficult to realize practically. Also, that method does not consider the impact of error concealment.

[08] In “Optimal mode selection and synchronization for robust video communications over error-prone networks,” IEEE Journal on Selected

Areas in Communications, vol. 18, no. 6, pp. 952–965, 2000 by Cote, et al., the optimal error resilience insertion problem is divided into two sub-problems: optimal mode selection for MBs; and optimal resynchronization marker insertion. That optimization is conducted on an MB basis and inter-frame dependency is not considered.

[09] Another method described by Zhang, et al., “Video coding with optimal inter/intra-mode switching for packet loss resilience,” IEEE Journal on Selected Areas in Communications, vol. 18, no. 6, pp. 966–976, 2000, determines recursively a total decoder distortion with pixel-level precision to account for spatial and temporal error propagation in a packet loss environment. That method attempts to select an optimal MB encoding mode. That method is quite accurate on the MB level when compared with other methods. However, that method does not consider the inter-frame dependency and the optimization is only conducted on the current MB.

[010] Dogan, et al. describe a video transcoding framework for general packet radio service (GPRS) in “Error-resilient video transcoding for robust inter-network communications using GPRS,” IEEE Transactions on Circuits and Systems for Video Technology, vol. 12, no. 6, pp. 453–464, 2002. However, the bit allocation between inserted error resilience and the video encoding is not optimized in that method.

[011] For video distortion caused by channel errors, a low complexity video quality model has been described by Reibman et al., in “Low-complexity quality monitoring of MPEG-2 video in a network,” in Proceedings IEEE International Conference on Image Processing, September 2003. However,

the measurement to determine error propagation effects is only based on the received bitstream. One of the most important aspects that is not fully considered by that method is the issue of inter-frame dependency, which is a key factor in motion compensated video encoding. Often, bit allocation and encoding mode selection are optimized only for the current MB or the current frame.

[012] It is desired to provide an optimal solution that reduces the video bit rate while maintaining error resilience. It is also desirable to have models that account for inter-frame dependency, which is inherent to many coding schemes, and also accurately account for the propagation of errors at the receiver. This is especially important when a video bit stream is transferred from a channel with a high bandwidth and a low bit-error-rate (BER), for example, a wired channel, to a channel with a low bandwidth and a high BER, for example, a wireless channel. For such a low bandwidth channel, the combined task of bit rate reduction and error resilience insertion is essential because the bit rate reduction needs to be balanced against the additional error resilience bits.

Summary of the Invention

[013] The invention provides accurate rate-distortion (R-D) models for transcoding videos. One model describes the rate-distortion characteristics for requantizing a video considering inter-frame dependencies. Other models estimate the distortion relationship for error propagation in a motion compensated video and characterizes the rate for intra-block and

resynchronization marker insertion. These models are used for optimal bit allocation schemes for video transcoding.

Brief Description of the Drawings

[014] Figure 1 is a block diagram of rate-distortion models and a transcoding method according to the invention;

[015] Figure 2 is a block diagram of a video transcoder according to the invention;

[016] Figure 3 is a block diagram of a video system according to the invention;

[017] Figure 4 is a block diagram of a spatial concealment method used by the invention;

[018] Figures 5 and 6 are block diagrams of decomposing distortion for I- and P-frames of a video caused by channel errors;

[019] Figure 7 is a graph comparing resynchronization marker insertion accuracy; and

[020] Figure 8 is a graph comparing intra-block insertion accuracy.

Detailed Description of the Preferred Embodiment

[021] As shown in Figure 1, the invention provides a method for transcoding 100 an input video bitstream 101 so that a bit rate in an output bitstream 102 is reduced while maintaining error resilience under a given bit rate constraint and channel condition. The method 100 subjects to input video to three rate-distortion (RD) models: a video source requantization model 111, an intra-block refresh model 112, and a resynchronization marker model 113. The outputs of the three models are input to a bit allocation control module 120, which determines a quantization parameter 121, a resynchronization marker rate 122 and an intra-block refresh rate 123. These parameters are used by a transcoder 130 to form the output bitstream 102.

[022] The three models are novel in that inter-frame dependency is included in both a video source model and an error resilience model. In addition, the error resilience model in the transcoding considers error concealment at the receiver.

[023] The invention also provides an alternative embodiment of the transcoding method that achieves near-optimal performance at a lower complexity.

[024] Transcoder Structure

[025] Figure 2 shows a transcoder 200 according to the invention. The transcoder includes a decoder 210 and an encoder 220. The decoder 210 takes an input video bitstream 101 at a first bit rate. The encoder produces an output

bitstream 102 at a second bit rate. In a typical application, the second bit rate is less than the first bit rate.

[026] The decoder 210 includes a variable length decoder (VLD) 211, a first inverse quantizer (Q^{-1}_1) 212, an inverse discrete cosine transform (IDCT) 213, a motion compensation (MC) block 214, and a first frame store 215.

[027] The encoder 220 includes a variable length coder (VLC) 221, a quantizer (Q_2) 222, a discrete cosine transform 223, a motion compensation (MC) block 224, and a second frame store 225. The transcoder also includes a second inverse quantizer (Q^{-1}_2) 226 and a second IDCT 227.

[028] In addition, the encoder includes an intra/inter switch 228 and a resynchronization marker insertion block 229.

[029] The bit allocation 120 of Figure 1 provides the quantization parameter 121 to the quantizer 222, the resynchronization marker rate 122 to the resynchronization marker insertion block 229 and the intra-block refresh rate 123 to the intra/inter switch 228.

[030] Problem Statement

[031] It is an object of the invention to minimize an end-to-end distortion of the encoded video bitstream subject to rate constraints. An overall rate budget is allocated among the three different components that contribute to the rate, i.e., video source requantization, resynchronization marker insertion, and intra-refresh.

[032] To achieve this object the three distinct components, the video source requantization model, the intra-refresh model, and the resynchronization marker insertion model are described. The later two model error-resilience. Although there is some degree of dependency among these three components, each component has a unique impact on the R-D characteristics of the transcoded video under different channel conditions.

[033] The video source model accounts for the R-D characteristics of the video bitstream without resynchronization markers or intra-refresh insertion, while the error-resilience models accounts for the R-D characteristics of intra-block insertion and resynchronization marker insertion.

[034] Although the separation of the error resilience model from the video source model is an approximation, it turns out to be quite accurate for the R-D optimized bit allocation scheme according to the invention.

[035] The problem is formally stated as follows. A target bit rate constraint is R_T . A total distortion is D , which is measured as a mean squared error (MSE). Given these parameters, it is desired to minimize the distortion, subject to the target rate constraint, i.e., to solve

$$\begin{aligned} \min \quad & D = \sum_{k=1}^K d_k(\omega_k) \\ \text{subject to} \quad & \sum_{k=1}^K r_k(\omega_k) \leq R_T, \end{aligned} \tag{1}$$

[036] where d_k is the distortion caused by each of the three components $k \in K$ for $k = 1, 2, 3$, r_k is the rate of each component and ω_k are the specific parameters used in the allocation, e.g., quantization parameters, resynchronization marker spacing, and intra refresh rate.

[037] One way to solve the above problem is through a Lagrangian optimization approach in which the following quantity is minimized:

$$\sum_{k=1}^K d_k(\omega_k) + \lambda \sum_{k=1}^K r_k(\omega_k), \quad (2)$$

[038] where λ is the Lagrangian multiplier to be determined during the optimization. A bisection process can be used to obtain the optimal multiplier used to solve this problem. However, that process is iterative and computationally expensive. Also, obtaining accurate R-D sample points required by the optimization procedure is still an open issue.

[039] It is preferred to use a distinct R-D model for each of the three components so that the optimization does not have to obtain the actual R-D values from simulation. With these models, some of the computational burden for solving the above problem is alleviated. However, this solution is relatively complex. Therefore, an alternative method that can solve the bit allocation problem with similar performance, but with a much lower complexity, is sought and described as part of this invention.

[040] Video Source Requantization Model

[041] Our R-D model for a coded video source operates on groups-of-frames (GOP). This accounts for inter-frame dependency by considering the requantization distortion in the current frame that propagates to the next frame through motion compensation. The R-D model is then modified accordingly for the next frame to account for this error propagation effect.

[042] If a composite signal, such as the output video 102 is decomposed into independent components, i.e., the requantized video, the resynchronization markers, and the intra-refresh blocks, then a composite R-D model can be derived directly from the three individual R-D models. Furthermore, if the signal can be decomposed into independent identically distributed (i.i.d.) Gaussian sources with energy compact transforms, such as the DCT, then the total distortion D of the signal caused by the encoding can be modeled as:

$$D = \left[\prod_{i=0}^{L-1} \Phi(\omega_i) \right]^{1/L} \cdot e^{-\beta \cdot R(D)}, \quad (3)$$

[043] where L is the total number of frequency coefficients in the case of DCT, $\Phi(\omega_i)$ is the power spectrum density function of coefficient i , R is the bit rate of the signal, and a constant parameter β is $2\ln 2$. An interesting observation from this result is that the exponential function of rate is proportional to the product of the coefficient variances rather than the sum of variances.

[044] The above model is only accurate for Gaussian sources with fine quantization. It is known that a video source can be characterized more

accurately by a generalized Gaussian model. Furthermore, a video source often needs to go through coarse requantization during transcoding to adapt to lower bandwidth constraints.

[045] The following modifications are made to the model to accommodate these two issues. First, the parameter β is made *variable*, rather than a *fixed* value, and second, $R(D)$ is replaced by $R^\gamma(D)$.

[046] Furthermore, if the value $[\prod_{i=0}^{L-1} \Phi(\omega_i)]^{1/L}$ is replaced by σ^2 , the total variance of the signal, then

$$D = \sigma^2 e^{-\beta R^\gamma(D)}. \quad (4)$$

[047] Experimental data indicate that β is usually in the range of $[1, 10]$, and γ is in the range of $[0, 1]$. Then, for requantizing intra-coded frames, the distortion is

$$D_0 = \sigma_0^2 e^{-\beta_0 R_0^{\gamma_0}}, \quad (5)$$

[048] where D_0 is the distortion of the intra-coded frame caused by requantization, and R_0 is the rate. The intra-coded variance, σ_o^2 , can be estimated in the frequency domain.

[049] It is possible to estimate the model parameters β and γ from two sample points on the R-D curve, as described herein.

[050] Without considering inter-frame dependency, a similar model can be used for inter-coded frames:

$$D_k = \sigma_k^2 e^{-\beta_k R_k^\gamma}, \quad k = 1, 2, \dots, N-1, \quad (6)$$

[051] where N is the total number of frames in a GOP, D_k is the distortion of the inter-coded frame caused by requantization, R_k is the rate and σ_k^2 is the variance of the input signal. Again, the model parameters β and γ can be estimated from two sample points on the R-D curve.

[052] The inter-frame dependency is modeled by changing the frame variance σ_k^2 to σ_k^{*2}

$$D_k = \sigma_k^{*2} e^{-\beta_k R_k^\gamma} = (\sigma_k^2 + \alpha_k D_{k-1}) e^{-\beta_k R_k^\gamma}, \quad k = 1, 2, \dots, N-1, \quad (7)$$

[053] where $\sigma_k^{*2} = \sigma_k^2 + \alpha_k D_{k-1}$ denotes the inter-frame variance, and D_{k-1} denotes an extra quantization residue error produced when the previous frame is requantized with a larger Q-scale, and α_k denotes a propagation ratio, which is determined by the amount of motion compensation. The term $\alpha_k D_{k-1}$ models the dependency between the current and the previous frame. This term captures the quantization error propagation effect caused by motion compensation. That is, when the previous frame is quantized coarsely, more quantization error propagates to the current frame through motion compensation.

[054] Model Parameter Estimation

[055] Parameter estimation for the proposed R-D models is performed in two stages on a GOP-basis. In the first stage, all the frames in the GOP are requantized with multiple sample quantization scales, e.g., 4, 8, 31. For the P-frames, no motion compensation is performed. Using the three sample R-D points, the three parameters σ_0^2 , β_0 , and γ_0 are determined from Equation (5) that establish the model for I-frame. Similarly, the parameters σ_k^2 , β_k , and γ_k

are estimated from Equation (6) that establish the model for P-frame without taking the propagation effect into account, i.e., the σ_k^2 that is estimated here denotes the variance of the input signal.

[056] The second stage takes care of propagation effects in the model parameter estimates for the P-frames by determining α_k . To do this, first requantize the I-frame at a different quantization scale than used in the first stage, e.g., $Q_I = 14$. Second, requantize the P-frames at a different quantization scale while performing motion compensation to account for the propagation effects. With one sample point in a P-frame, the parameter α_k^{*2} can be estimated from Equation (7). Then, from Equation (7), where $\sigma_k^{*2} = \sigma_k^2 + \alpha_k D_{k-1}$, determine α_k by:

$$\alpha_k = \frac{\sigma_k^{*2} - \sigma_k^2}{D_{k-1}}, \quad (8)$$

[057] where D_{k-1} is the distortion of the previous frame.

[058] The parameters γ_k and α_k are relatively constant within a given sequence. Therefore, it is sufficient to estimate these parameters only once at the start of a sequence, or if a scene change is detected. For parameters that are more sensitive to the scene content, e.g., σ_k and β_k , their values are updated for each frame. The advantage of this simplification is that after γ_k and α_k are estimated at the start, the transcoding only needs to be performed once to determine the model parameters, instead of twice. The parameter $\{\sigma_k^2\}$ is estimated from the variance of the DCT coefficients as expressed in Equation (4), and $\{\beta_k\}$ is estimated from one R-D sample point, which is easily obtained by requantizing the current frame.

[059] Error-Resilience R-D Models

[060] This section describes the second and third rate-distortion models that improve error-resilience, i.e., resynchronization marker insertion and intra-block refresh. First, a transmission environment is described, including the system structure, type of channel, and methods of error concealment. Then, the distortion models for resynchronization and intra-block insertion (intra-refresh) are described. Here, the focus is on the distortion models, because the rate estimates are obtained in a rather straightforward manner. Specifically, the rate consumed by resynchronization markers can be determined from the number of bits in the resynchronization header and the resynchronization marker spacing, while the rate consumed by intra-refresh can be determined from the intra-refresh rate and the average rate increase by replacing an inter-coded MB with an intra-coded MB.

[061] System Structure

[062] Figure 3 shows a system 300 for transmitting and receiving a video bitstream via a noisy channel. Audio data 301 is generated and multiplexed with encoded video data 302. The data are transmitted 310 according to the H.324M standard defined for a typical mobile terminal, and an AL3 TransMux defined in Annex B of the H.223 standard. A 16-bit and an 8-bit cyclic redundancy code (CRC) are used for error detection in the video and audio payloads, respectively. For video packetization, a packet structure described in the MPEG-4 resilience tool is used. This structure provides resynchronization at approximately the same number of bits. In this way, a typical video packet has seven bytes overhead in total, including two bytes for

control, three bytes for header, and two bytes for the CRC checksum. A maximum video packet payload length is 254 bytes.

[063] A wireless channel 320 is represented according to a binary symmetric channel (BSC) model, which assumes independent bit error 321 in a bitstream. For error detection, recovery and concealment in the video receiver 330, it is assumed that after an error is detected, either by a CRC checksum or by a video syntax check, the entire video packet containing the error is discarded, and the lost MBs are concealed. This is done to avoid disturbing visual effects caused by decoding erroneous packets. The receiver recovers the audio signal 303 and the video signal using a video decoder 304.

[064] Other errors that can be detected include illegal VLC, semantic error, excessive DCT coefficients (≥ 64) in a MB, and inconsistent resynchronization header information, e.g., QP out of range, $MBA(k) < MBA(k-1)$, etc. The error is recovered by resynchronizing to the added packet resynchronization markers or to the frame headers.

[065] For error concealment, both spatial and temporal error concealment methods are employed, using a simple block replacement scheme.

[066] As shown in Figure 4, a spatial concealment method is employed for a lost MB 401 in an intra-coded frame. The concealment is performed by copying the MB from its immediate upper neighbor 402.

[067] Similarly, temporal concealment is employed for a lost MB 410 in an inter-coded frame. Here, the motion vector 414 of the lost MB 410 is set to be

the median of the motion vectors selected from three specific neighbors, i.e., blocks labeled a 411, b 412, and c 413 as shown in Figure 4. The MB in the previous frame 415 that this motion vector is referencing is copied to the current location to recover the lost block 410.

[068] It is noted that the error-resilience models described in this invention also apply to other prior art error concealment schemes as well.

[069] Overall Distortion from Channel Error

[070] Figures 5 and 6 show the decomposition of the overall distortion for I- and P-frames caused by channel errors. A rectangle 501 denotes the set of all the MBs in an I-frame, while a rectangle 601 denotes the set of all MBs in a P-frame.

[071] For I- frames, distortion comes from lost intra-coded MBs (LS) 502, which are spatially concealed. For P-frames, distortion comes from two parts: distortion from lost MBs (L) 602, and distortion propagated from previous corrupted MBs through motion compensation, which are referred to as MC MBs 603. The lost MBs can be further decomposed into two categories: inter-coded MBs (LT) 604 lost and concealed with temporal concealment, and inter-coded MBs (LTC) 605 lost and concealed with temporal concealment, but the replacement themselves were corrupted. Note that LTC MBs define the intersection of L MBs and MC MBs. The MCC MBs 606 refer to the MBs that are received correctly, but reference the previous corrupted MBs through motion compensation.

[072] If the number of MBs lost in a frame is Y_l , the number of MBs corrupted through motion compensation is Y_{mc} , and the total number of MBs in a frame is M , then the average number of corrupted MBs in a frame $E[Y]$ can be expressed as:

$$E[Y] = E[Y_l] + E[Y_{mc}] - E[Y_{lmc}], \quad (9)$$

where $Y_{lmc} = Y_l \cap Y_{mc}$. This intersection is proportional to the number of lost MBs and the number of inter-coded MBs corrupted through motion compensation, and subsequently,

$$E[Y_{lmc}] = E[Y_l \cap Y_{mc}] \approx \frac{E[Y_l] \cdot E[Y_{mc}]}{M}, \quad (10)$$

[073] and the total average distortion, measured in MSE, can therefore be calculated by:

$$D = \begin{cases} \frac{1}{M} \{ E[Y_l] \cdot D_s \} & \text{for I - frame} \\ \frac{1}{M} \{ E[Y_{lt}] \cdot D_t + E[Y_{lmc}] \cdot D_{lc} + E[Y_{mcc}] \cdot D_{mc} \} & \text{for P - frame,} \end{cases} \quad (11)$$

[074] where D_s is the average spatial concealment distortion, D_t is the average temporal concealment distortion when copying a correct MB from the previous frame, D_{lc} is the average temporal concealment when copying a corrupted MB from the previous frame, and D_{mc} is the average distortion of correctly received MBs referencing corrupted MBs through motion compensation. The number of MCC MBs is Y_{mcc} as shown in Figure 5.

[075] Techniques to determine each quantity in the above equation are described below. There are two categories of quantities: distortion related to concealing lost MBs, and distortion related to error propagation as a result of motion compensation.

[076] Error Concealment Distortion

[077] The probability p_l that one MB is lost in a video frame n can be modeled by the probability p_{sl} that a video packet is lost. If the channel bit error rate (BER) is P_e , and an average video packet length in bits is L_s , then

$$p_l = p_{sl} = 1 - (1 - P_e)^{L_s}. \quad (12)$$

[078] It follows that the average number of lost MBs $E[Y_l(n)]$ in frame n is $p_l \cdot M$. The distortion caused by losing one MB can be calculated according to one of the three situations:

the loss of an intra-coded MB that is spatially concealed resulting in distortion D_s ,

the loss of an inter-coded MB that is temporally concealed by copying a non-corrupted MB from the previous frame resulting in distortion D_t , and

the loss of an inter-coded MB that is temporally concealed by copying a corrupted MB from the previous frame resulting in distortion D_{tc}

[079] The values D_s and D_t can be estimated by calculating pixel differences between the lost MB and the replacement MB. The value D_{tc} can be approximated by an addition of motion compensation corruption to D_t , e.g.,

$$D_{tc} = D_t + D_{mc}.$$

[080] Error Propagation Distortion

[081] A Markov model can be used to estimate error propagation by motion compensation. The reason for using the Markov model is because the number of corrupted MBs in the current frame through motion compensation only depends on the motion vectors in the current frame and the number of corrupted MBs in the previous frame. The probability that a single MB is corrupted through motion compensation can be determined by:

$$p_{mc} = \rho\theta_1 + [1 - (1 - \rho)^2]\theta_2 + [1 - (1 - \rho)^4]\theta_3, \quad (13)$$

[082] where ρ is the probability of one MB being corrupted in the previous frame, θ_1 denotes the proportion of MBs in the current frame that reference a single MB, θ_2 denotes the proportion of MBs that reference two MBs, and θ_3 denotes the proportion of MBs that reference four MBs in the previous frame. If the proportion of intra-coded MBs is denoted η , then $\theta_1 + \theta_2 + \theta_3 + \eta = 1$. From this relation, it is clear that a higher value of η yields a lower value of p_{mc} .

[083] Then, a probability transition matrix that characterizes the error propagation through motion compensation can be calculated by:

$$P(i, j_{mc}) = P\{Y_{mc}(n) = j_{mc} | Y(n-1) = i\} = \begin{pmatrix} M \\ j_{mc} \end{pmatrix} p_{mc}^{j_{mc}} (1 - p_{mc})^{M-j_{mc}}, \quad i, j_{mc} = 0, \dots, M. \quad (14)$$

[084] where j_{mc} is the number of MBs corrupted through motion compensation in frame n , i is the total number of MBs corrupted in frame $n - 1$. An n -step probability transition matrix \mathbf{P}^n is:

$$\mathbf{P}^n = \prod_{k=1}^n \mathbf{P}_k, \quad (15)$$

where

$$\mathbf{P}^n(i, j_{mc}) = P\{Y_{mc}(n) = j_{mc} | Y(0) = i\}. \quad (16)$$

[085] \mathbf{P}^k is the 1-step Markov transition matrix for frame k . The average number of corrupted MBs through motion compensation in frame n can be obtained by

$$P^n(i, j_{mc}) = P\{Y_{mc}(n) = j_{mc} | Y(0) = i\}. \quad (17)$$

[086] where $p_0(i)$ is the probability of i MBs being corrupted in the first frame.

[087] The above model is computationally complex, and is therefore simplified using a 1-step Markov model instead of an n -step Markov model, and use $E[Y(n)]$ to replace i in Equation (14). Therefore, Equation (17) becomes

$$E\{Y_{mc}\} = M \cdot p_{mc}. \quad (18)$$

[088] It follows that the average distortion due to motion compensation at frame n can be expressed by

$$D_{mc}(n) = \rho \cdot (1 - \eta) \cdot D(n - 1), \quad (19)$$

[089] where $D(n - 1)$ is the average distortion of frame $n - 1$.

[090] Model Accuracy

[091] Figure 7 compares the accuracy of the R-D model for resynchronization marker insertion as a function of marker spacing or video

packet length. The rate change of inserted resynchronization markers comes from the change of marker spacing or packet length in a range of [130, 1300] bits. The test is performed with a channel BER = 10^{-4} .

[092] Figure 8 shows a test of the intra-refresh R-D model as a function of intra-refresh rate. The intra-refresh rate varies from 2% to 90%. From these figures, it can be seen that the error-resilience models according to the invention predict accurately the actual distortion.

[093] Bit Allocation

[094] Based on the above described R-D models for video source requantization, resynchronization marker insertion, and intra-refresh, it is now possible to solve the R-D optimized bit allocation problem. Then, the resulting optimal source R-D curve can be used in the overall bit allocation for error resilient coding. Based on the overall optimal bit allocation scheme, a sub-optimal scheme to enable transcoding with lower complexity, but achieving similar performance, is described.

[095] Optimized Rate Allocation- Source Requantization Only

[096] With the R-D model for video source requantization, optimal bit allocation 120 can be achieved for a given rate budget R . Specifically, a solution to the following problem is sought:

$$\begin{aligned}
& \min \quad \sum_k D_k \\
& \text{subject to} \quad \sum_k R_k \leq R \quad \text{and} \quad R_{kl} \leq R_k \leq R_{ku} \quad k = 0, 1, \dots, N-1
\end{aligned} \tag{20}$$

where R_{kl} and R_{ku} are lower and upper bound of the achievable rate for the k^{th} frame.

[097] For an I-frame, R_{kl} and R_{ku} can be determined by the minimum and maximum allowable quantization scale. For a P-frame k , R_{kl} is achieved by assigning a minimum quantization scale to all its previous frames (0 to $k-1$), and the maximum allowable quantization scale to the current frame. On the other hand, R_{ku} is obtained by assigning a maximum allowable quantization scale to all its previous frames and the minimum quantization scale to the current frame. In practice, R_{ku} can be estimated by coding all the MBs in the current frame with intra mode.

[098] There are several known methods to solve the above optimization problem, e.g., a dynamic programming approach based on the Lagrange multiplier and a trellis. The problem with that approach is that as the number of frames increases, the trellis grows exponentially and the size of the problem quickly becomes intractable. Another issue is that the Lagrange multiplier needs to be determined by traversing the trellis tree iteratively, which further complicates the problem. An alternative approach incorporates a penalty function into the minimization problem. However, that iterative approach is relatively complex. Both approaches assume that the actual R-D values at various operating points are readily available, which may not be the case in practical applications.

[099] The method according to the invention is based on a projected Newton method, see Bertsekas, “Projected Newton methods for optimization problems with simple constraints,” Tech. Rep. LIDS R-1025, MIT, Cambridge, MA, 1980, incorporated herein by reference.

[0100] In order to use that method, the problem in Equation (20) needs to be modified. First, an optimal minimum distortion occurs when $\sum_k R_k = R$, i.e., the optimal solution always uses the entire available bit budget. Second, it is practical to achieve a lower bit budget, most of the time. Therefore, the rate upper bound R_{ku} is exceeded rarely. Thus, the upper bound can be eliminated. Given this, the new constrained problem is written as:

$$\begin{aligned} \min \quad & \sum_k D_k \\ \text{subject to} \quad & \sum_k R_k^* = R^* \quad \text{and} \quad R_k^* \geq 0 \quad k = 0, 1, \dots, N-1 \end{aligned} \quad (21)$$

[0101] where the lower bound R_{kl} is eliminated by substituting R_k with $R_k^* + R_{kl}$, where $R^* = R - P_k R_{kl}$.

[0102] One advantage of this method is that no additional parameters need to be introduced, such as a Lagrangian multiplier. The constraints are handled implicitly within the method by variable substitution and linear projection. Therefore, this method is comparable to its unconstrained counterpart. Another advantage of the method is that it uses Hessian information to improve the convergence. Therefore, the resulting Newton-like method has a typically superlinear rate of convergence and is considerably faster than prior art methods. With this method, the size of the

problem can be increased considerably without increasing the computational time.

[0103] R-D Derivative Equalization

[0104] To provide a low-complexity implementation for the bit allocation, a technique to determine a suboptimal operating point is described. This technique is basically an R-D derivative equalization scheme. This scheme is based on the fact that optimal bit allocation is achieved at the point where the slopes of the R-D function for each component are equalized, i.e., made substantially the same.

[0105] Starting from an operation point close to an optimal point, the objective is to continually adjust the operating point in the direction of the optimal point. To achieve this, there are two steps:

start from an operational point close to the optimal point, and move towards an optimal point and remain at that point, given changes in video content and channel conditions.

[0106] The first step is not very difficult because the initial optimization only needs to be done with the first GOP. The second step uses the following R-D derivative equalization scheme. Specifically, examine a local derivative of each R-D curve and adjust the bits allocated to each component accordingly. If the rate budget is constant, then reallocating a change in rate ΔR from the component with a smallest absolute derivative value to the component with a largest absolute derivative value is a good approximation to the optimal solution.

[0107] Bit Allocation Strategy

[0108] In order to evaluate the rate allocation strategy as described above, the following ancillary models are provided. The number of multiple transcoding components is N , with component i operating at bit rate R_i and a distortion D_i . The total distortion is given by $D = \sum_{i=1}^N D_i(R_i)$, and a total rate is given by $\sum_{i=1}^N R_i$. We assume that all R-D functions are convex, and $dD_i / dR_i \leq 0$, for all $i = 1, \dots, N$.

[0109] In one interpretation of the problem, we are given an additional rate $\Delta R \geq 0$. The goal is to allocate among the components so that the total distortion D is maximally decreased. If ΔR is relatively small, then the total change in distortion, ΔD , can be expressed as:

$$\Delta D = \sum_{i=1}^N \left(\frac{dD_i}{dR_i} \cdot \Delta R_i \right) \geq \frac{dD_k}{dR_k} \cdot \sum_{i=1}^N \Delta R_i = \frac{dD_k}{dR_k} \cdot \Delta R,$$

where $\left| \frac{dD_k}{dR_k} \right| \geq \left| \frac{dD_i}{dR_i} \right|$ and $\frac{dD_i}{dR_i} \leq 0 \quad \forall i = 1, \dots, N.$ (22)

[0110] In the above equation, the derivative dD_i / dR_i is replaced by the highest absolute value of derivative dD_k / dR_k , because $dD_i / dR_i \leq 0$. Therefore, the allocation scheme that best minimizes ΔD , or maximizes $|\Delta D|$, because $\Delta D < 0$, allocates all the additional bits to component k .

[0111] In a second interpretation of the problem, we decrease the total rate R by ΔR . In this case, ΔD can be expressed as:

$$\Delta D = \sum_{i=1}^N \left(\frac{dD_i}{dR_i} \cdot \Delta R_i \right) \geq \frac{dD_l}{dR_l} \cdot \sum_{i=1}^N \Delta R_i = \frac{dD_l}{dR_l} \cdot \Delta R,$$

where $\left| \frac{dD_l}{dR_l} \right| \leq \left| \frac{dD_i}{dR_i} \right|$ and $\frac{dD_i}{dR_i} \leq 0 \quad \forall i = 1, \dots, N.$ (23)

[0112] In the above equation, the derivative dD_i / dR_i is replaced by the lowest absolute value of derivative dD_l / dR_l . Therefore, the best bit allocation scheme that minimizes ΔD , decreases the rate of component l by ΔR .

[0113] In a third interpretation of the problem, we reallocate bits among the transcoding components without increasing or decreasing the total rate. To achieve this, we increase the rate of some components. We denote this group with current operation rate R_{ik} and distortion D_{ik} , wherer $ik \in [1, N]$. We also decrease the rate of the remaining components. We denote this group with current operation rate R_{il} , and distortion D_{il} , where $il \in [1, N]$. The rate increase ΔR_{ik} , and the rate decrease ΔR_{il} should satisfy the three conditions below:

$$(i) \sum_{\Delta R_{ik} \geq 0} \Delta R_{ik} = \Delta R, \quad (ii) \sum_{\Delta R_{il} \leq 0} \Delta R_{il} = -\Delta R, \quad (iii) \Delta R > 0, \quad (24)$$

[0114] where ΔR is the total rate adjustment. Then, the total change in distortion can be expressed as:

$$\begin{aligned}
\Delta D &= \sum_{\Delta R_{ik} \geq 0} \frac{dD_{ik}}{dR_{ik}} \cdot \Delta R_{ik} + \sum_{\Delta R_{il} \leq 0} \frac{dD_{il}}{dR_{il}} \cdot \Delta R_{il} \\
&\geq \frac{dD_k}{dR_k} \sum_{\Delta R_{ik} \geq 0} \Delta R_{ik} + \frac{dD_l}{dR_l} \sum_{\Delta R_{il} \leq 0} \Delta R_{il} = \frac{dD_k}{dR_k} \cdot \Delta R - \frac{dD_l}{dR_l} \cdot \Delta R, \\
\text{where } \left| \frac{dD_k}{dR_k} \right| &\geq \left| \frac{dD_{ik}}{dR_{ik}} \right|, \quad k \in \{ik\}, \quad \text{and} \quad \left| \frac{dD_l}{dR_l} \right| \leq \left| \frac{dD_{il}}{dR_{il}} \right|, \quad l \in \{il\}.
\end{aligned} \tag{25}$$

[0115] From the above equation, it can be seen that the optimal bit reallocation scheme to minimize distortion should be the one that deducts ΔR only from the component with the smallest absolute derivative value, and adds ΔR only to the component with the largest absolute derivative value.

[0116] An additional point that needs to be addressed here is the optimal value of ΔR . Because the value order of the derivatives dD_i / dR_i for $i = 1, \dots, N$ should not change, we select the largest possible value that keeps Eqs. (22), (23) and (25) valid.

[0117] This method has a lower cost than the global optimal method. The entire R-D curve for each encoding component is not required. In this embodiment, two local sample points on the R-D curve can be used to perform a discrete differentiation.

[0118] Sub-Optimal Bit Allocation Procedure

[0119] The following procedures are implemented to facilitate a low-complexity transcoding operation. For the first GOP of the video sequence,

the model parameters are estimated and the R-D models for the video source requantization, resynchronization marker insertion and intra-refresh are established.

[0120] Then, optimal bit allocation can be achieved for this GOP through Lagrangian optimization process as described above. For each subsequent GOP, simplified parameter estimation procedures are used to generate two local operation points. Then, a local derivative is obtained by discrete differentiation. If local derivatives of the three R-D curves are equal, then the current bit allocation is retained. Otherwise, the bit allocation of the component with the largest absolute value local derivative is increased, and decrease the bit allocation of the component with the lowest absolute value local derivative.

[0121] Effect of the Invention

[0122] The invention provides rate-distortion D models that consider inter-frame dependency for optimal bit allocation in error resilient video transcoding. A sub-optimal scheme achieves similar performance with much lower complexity. Overall, the method according to the invention with *variable* bit allocation has superior performance compared to error-resilient transcoding schemes with *fixed* bit allocation.

[0123] Although the invention has been described by way of examples of preferred embodiments, it is to be understood that various other adaptations and modifications may be made within the spirit and scope of the invention. Therefore, it is the object of the appended claims to cover all

such variations and modifications as come within the true spirit and scope of the invention